Circulation Variations in the Northern Main Basin of Puget Sound

Glenn A. Cannon
School of Oceanography, University of Washington

Curtis C. Ebbesmeyer
Evans-Hamilton, Inc.

Bruce J. Nairn
King County Department of Natural Resources

Abstract
This paper describes measured currents in an ongoing study of the Triple Junction, and it assesses causes and effects of major flow variations. Understanding the circulation is important because it either flushes pollutants from the Sound or redistributes them within it. Three main points are reported here: the topography constrains a meandering surface outflow; winds cause flow events into Possession Sound; and dissolved oxygen is low in Whidbey Basin. Other results are being reported in a series of interim reports to King County. It should be noted that the ongoing observations are taking place during an unusually dry year, and there may be large effects due to the low runoff.

Introduction
Puget Sound is a fjord estuary that connects to the Strait of Juan de Fuca through Admiralty Inlet. The Whidbey Basin connects to the Main Basin at the junction with Admiralty Inlet. There have been relatively few studies in this region, also called the Triple Junction. Important flow characteristics include tidal and wind forcing, estuarine circulation, and coastal ocean variations at the entrance to the Strait. Inflow of salt water at depth keeps the Sound from stagnating; outflowing surface water flushes the Sound. The difference between the two is a net outflow equal to the input of the rivers. Mixing by tides and winds and over the Admiralty Inlet sill plays a major role in this process. Most previous studies focused on the along-channel effects. The few cross-channel studies have shown significant variations that affect how waters mix, and they suggest that the core of maximum outflowing water meanders through the northern Main Basin. Further complexity in the Triple Junction is caused by the large shoal off Whidbey Island. It is important to understand the along- and across-channel flow variations in this region because prevailing currents would affect the fate of discharge from a potential new sewer outfall. Additional observations are being made through a yearlong study extending from July 2000 to July 2001.

This paper describes a sample of the current state of knowledge of the oceanography that affects the Triple Junction prior to the present study, and it describes preliminary results from the new observations. The emphasis is on mean flow (tidal averages) and wind caused variations. Other important flow variations caused by salt-water intrusions from the Strait of Juan de Fuca, river flow variations from the Skagit and Snohomish rivers, and tidal eddies are not discussed in this paper. A more extensive review of prior studies, with references, and the most recent summary of preliminary results from the ongoing study are in Ebbesmeyer and Cannon (2001a and 2001b).

Observations
Figure 1 is a chart of Puget Sound showing historic current moorings and CTD stations. Puget Sound is a deep fjord estuary, and depths exceed 200 m in much of the Main Basin. There are two shallower sills in Admiralty Inlet, but none at the junction with Possession Sound. The chart shows that there are relatively few observations in the Triple Junction. Three sections across Admiralty Inlet and the northern Main Basin are described in Figure 2. [Editor's note: All figures occur at the end of this paper, following the references section.] The locations of the moorings in the ongoing study are shown in Figure 4.

Figure 2 shows cross-channel mean currents in Admiralty Inlet, at Point Wells and at Meadow Point. The flow in Puget Sound is dominated by tidal currents, but superimposed on that is a time-varying estuarine circulation caused by the surface outflow of fresh water from river runoff and deep inflow of salt water from the ocean. The estuarine circulation is important in transporting water masses and is typically up to about 10 cm/sec, but it can be larger during storms and bottom-water intrusions. The estuarine circulation has been determined at various locations from current meter observations by numerically filtering the tidal currents and then averaging over the total period of the observations. The resulting net flows in most of the Sound are seaward near the surface and landward near the sea floor. The depth of the change from the seaward to landward flow is the level of no net motion.

Historically, current meters were usually placed at mid channel to obtain measurements of the along-channel flow. Studies at various times of the cross-channel variability in Admiralty Inlet, off Point Wells and off Meadow Point, however, showed that single moorings at mid channel did not adequately represent the flow. Three to five moorings placed across channel were found necessary to resolve the variations of the along-channel flow through the sections. Often the flow was concentrated along one side of the channel.

Three moorings across Admiralty Inlet at Bush Point for about a month in 1977 showed a sloping level of no motion. The slope was from about 30 m on the east to about 70 m on the west, and it is opposite that caused by the earth’s rotation. This implies that the channel curvature has a large effect on the flow, and the larger outflows are in the middle and on the west side.

The transect at Point Wells is a composite from short-term mooring observations (2 to 6 days) in two different years (1982, 1999). It shows higher outflows concentrated from the middle toward the eastern shore off Point Wells. The level of no-net-motion slopes downward to the east, characteristic of the earth’s rotation effect, and possibly intersects the bottom near 80 m. This implies that off Point Wells there is a net outflow at all depths shallower than about 80 m. An ADCP (Acoustic Doppler Current Profiler) was deployed at a depth of about 70 m on the east side in 1999, and it confirmed outflow at all depths at that site. This figure also shows relatively high speeds near the surface. The relatively short measurements occurred during northerly winds that are known to increase the surface outflow (shown later in Figure 6). The long-term averages for the middle mooring had a smaller surface outflow, and it can be inferred that the long-term flow through the section in Figure 4 also would be less.

The section off Meadow Point was investigated with 5 moorings including 2 near-surface current meters. The higher outflow occurred from the middle to the west side, indicating that curvature effects were more important than the earth’s rotation. The eastern most mooring showed southward flow at all depths, probably caused by an eddy north of West Point. The maximum outflow speeds were about the same as those in Admiralty Inlet, but less than off Point Wells, further indicating the probable wind effects on the short-term observations at Point Wells.

Figure 3 is a schematic plan view of mean inflow and outflow in Puget Sound and Whidbey Basin. The schematic view joins the cross-channel transects in Figure 2. The major flow patterns consist of two-layered flow in the three branches joining at the Triple Junction (L), outflow from Colvos Passage (A), and inflow in East Passage (B). In addition, the outflowing surface water starting from Colvos appears to meander from side to side in the Main Basin in response to major topographic features. Higher speeds favor the east side near Alki Point (C) and Point Wells (E), and the west side near Point Monroe (D) and Apple Cove Point (F). This pattern can result in eddies behind major points with reversed flow near shore, e.g., near Meadow Point north of West Point.

The outflow from Whidbey Basin is concentrated in the upper 10-20 m (Figure 5). In the Main Basin at Point Wells, the outflow varies in depth from 70 m near Point Wells to 20 m on the western shore. How these two flows merge is a major unknown that must be understood in order to understand where the Sound’s currents would transport effluents discharged in the Triple Junction region. There have been relatively few current measurements in Possession Sound.

Deep water is also shown flowing into the Sound beneath the upper outflowing layer in Figure 3 (G). These flows are generally slower than the currents near the sea surface, a difference that varies substantially between the Sound's basins. Deep water in the Main Basin (M) often travels 5-10 times faster than deeper currents in Whidbey Basin (H) as a result of vigorous upwelling at The Narrows. The difference in flow speeds occurs as deep water diverges at the southern end of Admiralty Inlet (L); the Whidbey branch slowing down compared with the Main Basin flow.

Figure 4 is a map of observed mean currents at 20 m with schematic interpretations (July through October 2000). The figure represents our present understanding of the mean flow in the shallower (20 m) waters of the Triple Junction based on 28-day mean vector currents. The 20-m level was selected because it is the approximate effluent trapping depth previously determined for the West Point sewage treatment plant. The shoals south of Whidbey Island average about 50 m, so that the 20-m map lies above it. Net currents over 28-day intervals were computed from each current meter record, and the number of 28-day intervals per deployment varied because of the different durations of the three deployments. Note that the deeper trapping depth of 100 m for the Renton plant is not discussed here (See Ebbesmeyer and Cannon 2001b).

Changes in the vectors provide an indication of the spatial and temporal variability of the mean currents. In Possession Sound mid-channel currents at these depths are small and variable, but in the Main Basin there are more clearly defined outflow and inflow regimes. Temporal variations are shown by the varying net vectors from the 28-day averages at each deployment site, and schematic interpretations of the mean flow are shown by different colored arrows. Note that the vectors from the moorings are to scale, but the inferred flow arrows are not scaled for speed and are intended only to illustrate the flow pattern. The following narrative is a draft interpretation of our best estimate of the flow pattern as an aid to further selection of mooring locations and to guide further data analysis.

In general, the outflowing waters from Whidbey and Main basins converge along the eastern flanks of Whidbey Shoals between Moorings 10 and 13, with Mooring 16 located in about the center of the convergence. At this location the net vectors head northwest perpendicular to the bathymetry in the vicinity of where the King County model showed upwelling.

Between Moorings 11 and 17, the flows converge or head toward one another. From there, some water heads toward shore where it diverges along shore between Moorings 12 and 18. This onshore flow may partially explain why so many drift cards beach between Mooring 12 and Edwards Point. North of Edwards Point the flow diverges as it enters the wider areas of the Triple Junction. This creates a weak back flow just north of Edwards Point and a back flow southward along the Kitsap Peninsula.

Details of the flow may be described as follows:

a. The core of strongest mean flow compresses as it impinges on the shore in the vicinity of Point Wells.

b. North of Edwards Point the flow diverges as it enters the wider areas in the Triple Junction. This creates a weak back flow just north of Edwards Point and a back flow southward along the Kitsap Peninsula (see items l, m).

c. Outflow from Possession Sound intensified on the western shore containing fresh water outflowing from Whidbey Basin.

d. Outflowing Possession Sound less saline water continues westward across Whidbey Shoals.

e. Convergence of Whidbey and Main basin flows in the vicinity of Mooring 16.

f. Convergence of Main and Whidbey basin flows between Moorings 11 and 17.

g. Onshore flow resulting from convergence between Moorings 11 and 17.

h. Northward alongshore flow north of Browns Bay.

i. Northward alongshore flow continues into Possession Sound.

j. Southward alongshore flow south of Browns Bay to Edwards Point.

k. Faster outflow from Triple Junction to Admiralty Inlet.

l. Divergence of Main Basin flow heading out Admiralty producing southward flow near shore.

m. Southward flowing current along Kitsap Peninsula.

Near (c) at approximately Mooring 13, the southward net currents average on the order of 5 cm/sec and transport most of the freshwater exiting Whidbey Basin. Note that the ADCP does not penetrate much above 20 m where much faster speeds are anticipated. Near (i) at approximately Mooring 14, the net current lies in the range of 0-2 cm/sec

Figure 5 shows profiles of mean currents in the Main Basin and Possession Sound (July-Sep 2000). The along-channel mean current profiles from the July and August ADCP deployment (D1) are compared with the first half of the August through October deployment (D2a). The vertical profiles also show what part of the water column is represented by the map of 20-m mean currents (Figure 4). Comparison between Aanderaa and ADCP currents have shown excellent agreement (Ebbesmeyer and Cannon 2000).

There are significant differences between the two sets of profiles. Possession Sound circulation resembles the middle reaches of a fjord where, in this case, the sill is far downstream at Admiralty Inlet and the river input is far upstream beyond Possession Sound. The level of no motion is very near the 20-m Aanderaa. The two deployments overall are very similar. But, during July and August, there is a net inflow at 20 m and a weaker surface outflow. During August and September the 20-m flow was zero. Because of the lack of current meters between 20 m and 110 m, there is a large uncertainty of the depth and magnitude of the maximum inflow that could cause changes in the 20-m flow. The Main Basin flow is two-layered with zero velocity at about 80 m, and the profiles for the two deployments are basically identical. The merging in the Triple Junction of the flow patterns from these two different flow regimes is not yet fully understood, but a first description was presented in Figure 4. Further studies of the time variations in the flow should help better understand the process.

Figure 6 shows wind effects on mean currents in the Main Basin. There are two major forces, winds and bottom-water intrusions, which can cause significant variations in the tidally averaged mean circulation. This figure shows the predominate winds that are northward (to the north) during storms and southward during periods of good weather (Figure 6, lower panel). The northward winds augment the surface outflowing water, and the southward winds impede and sometimes reverse the surface flow (Figure 6, upper panel). However, these effects at the surface must have compensating flows (opposite direction), or there would be an accumulation of water in, or a draining of water from, the Sound. The middle panels of Figure 6 show this effect. The two daily averages have been subtracted from the long-term averages (Figure 2., lower panel), and the resulting differences are the changes caused by the winds. The surface changes are relatively large, 15-20 cm/sec, and the compensating flows, about 10 cm/sec, occur at mid depths of about 100 m. These major changes occurred on two days only one week apart. The relatively large surface outflow in the Point Wells section (Figure 2, middle panel) occurred during northward winds.

Bottom-water intrusions are not discussed here (See Ebbesmeyer and Cannon 2001a and b).

Figure 7 shows drogue trajectories at 20-30 m in the Main Basin and Possession Sound (October 2000). The trajectories are for 7 days for drogues released at 20-30 m at seven of the eight drift-card release sites (See Ebbesmeyer and Cannon 2001b). The sites are near shore and offshore at Carkeek Park (gold and green tracks), Point Wells (blue, none), Edmonds (pink, black), and Possession Point (yellow, orange). The near-shore drogue off Point Wells did not work. All but one of the trajectories (black) showed unusually long excursions along shore, and most of these (except gold) extended into Possession Sound. Three of the drogues (gold, blue, and pink) reversed direction in Possession Sound, and flowed south near the shore. The two drogues released off Possession Point at the southern entrance to Possession Sound (yellow and orange) did not reverse, but drifted into Port Susan. The gold trajectory may have grounded off Edmonds.

The offshore drogue at Edmonds (black) had a completely different trajectory that extended out Admiralty Inlet. It apparently was entrained into the mean outflow shown in Figure 4. The other drogues may have been trapped near shore by winds blowing from the south that caused the currents at 20-30 m to flow into Possession Sound as described below in Figure 8.

Figure 8 show time series of tidally averaged currents and winds in Possession Sound (July through Oct 2000). The along-channel currents are at 2 m and 26 m at the Possession Sound Aanderaa mooring, and the along-channel component of winds was measured nearby at Paine Field. This figure shows the high correlation between the winds and 2-m currents. The maximum outflow (minus) occurred with winds blowing to the south. Winds blowing from the south (generally associated with storms) significantly reduced the surface outflow, and almost reversed it on October 16. The two-layer circulation in Possession Sound is different than that in the Main Basin (Figure 5), and winds may be expected to affect the circulation differently than shown for the Main Basin (Figure 6).

The drogues (Figure 7) were deployed near the end of the current measurements and were during beginning of a northward current excursion. The flow at 26 m, at the depth of the drogues, reversed direction numerous times. This oscillation, about the long-term zero mean speed, disguised the substantial extent of the intrusions to the north and south. The inflow into Possession Sound started the day the drogues were deployed reaching a maximum of 2-3 cm/sec, and it lasted for about 4 days. The speeds and duration were sufficient to produce the observed excursions. The flow reversed to southerly during the rest of the deployment accounting for the reversed flow of the drogues.

If this relatively small current reversal caused the large drogue excursion into Possession Sound, the much larger reversal at the end of July could have caused an even larger mid-depth inflow. However, the correlation of the 26-m flow as a compensation flow to the wind effect on the surface is less clear due to the unknown depth of the maximum inflow during this time. Preliminary results from the next set of observations during November-January indicate that the wind may have its maximum compensation effect at depths of 85-115 m. Because the depth of the drogues was near the zero level of the mean current profiles, the effects of the winds may be harder to determine. But, flow at this level can have significant excursions into Possession Sound, and it is difficult now to relate these intrusions to the average currents (Figure 4). Thus, it is important to understand the time variations of the tidally averaged currents in the intrusion process. In addition, ADCPs may be deployed closer to the mid-channel Aanderaa mooring in a future deployment.

Figure 9 shows dissolved oxygen minima in the Main Basin and Possession Sound. Puget Sound waters are oxygenated to varying degrees by several sources and sinks. Sources include oxygen introduced by water flowing at depth from the Pacific Ocean, and oxygen produced by algal growth in the Sound's near-surface waters. Sinks include oxygen consumed by organic material descending through the water column and by organic processes within the bottom sediments.

Within the water column, diffusion and advection blend the effects of the sources to varying degrees depending on vertical and horizontal position within the Sound. Based on historical measurements obtained since 1932, the balance between oxygen production and consumption varies substantially within the Sound, causing the level of saturation to vary between approximately 10% in areas where consumption dominates over production, to 200% near the sea surface in summer where production dominates over consumption.

Throughout the year the surface marine waters remain well oxygenated, but beneath the photic layer (0-20 m), less oxygenated water flows through Puget Sound. Figure 9 traces the oxygen concentration of inflowing water through the study area. Between Point No Point and Point Jefferson, a secondary fraction (order of 10%) of the deep water diverges and doubles back northward into Whidbey Basin. Whereas water travels some 100 miles in about 3 weeks from Point No Point to the Main Basin's terminus at Tacoma, deep water requires about 2 months to traverse a comparable distance to the head of Whidbey Basin.

As the deep waters progress through the Sound, the load of organic material produced in the photic layer rains downward and consumes dissolved oxygen, thus lowering the concentrations along the flow paths southward through the Main Basin and northward through Possession Sound and Saratoga Passage. At Point No Point, the lowest seasonal values typically average 5.8 mg/liter and decreases as organic material consumes the oxygen. After a week or so, the water reaches Point Jefferson and the DO has decreased by

0.2 mg/liter to 5.6 mg/liter. Along the slower pathway through Whidbey Basin (30 meters depth), oxygen consumption decreases the values to 5.2 mg/liter off Possession Point. Between there and Port Gardner, oxygen decreases to 3.1 mg/liter.

Summary

The main points in this paper emphasized that: the topography of Puget Sound constrains a meandering surface outflow (Figures 3 and 4); winds cause major flow events into Possession Sound (Figures 7 and 8); and dissolved oxygen is low in Whidbey Basin (Figure 9). What's next? The observations will continue through mid-summer 2001. The interpretations will be updated with each set of new observations in a series of interim reports to King County, and a final report will be prepared for King County later this year.

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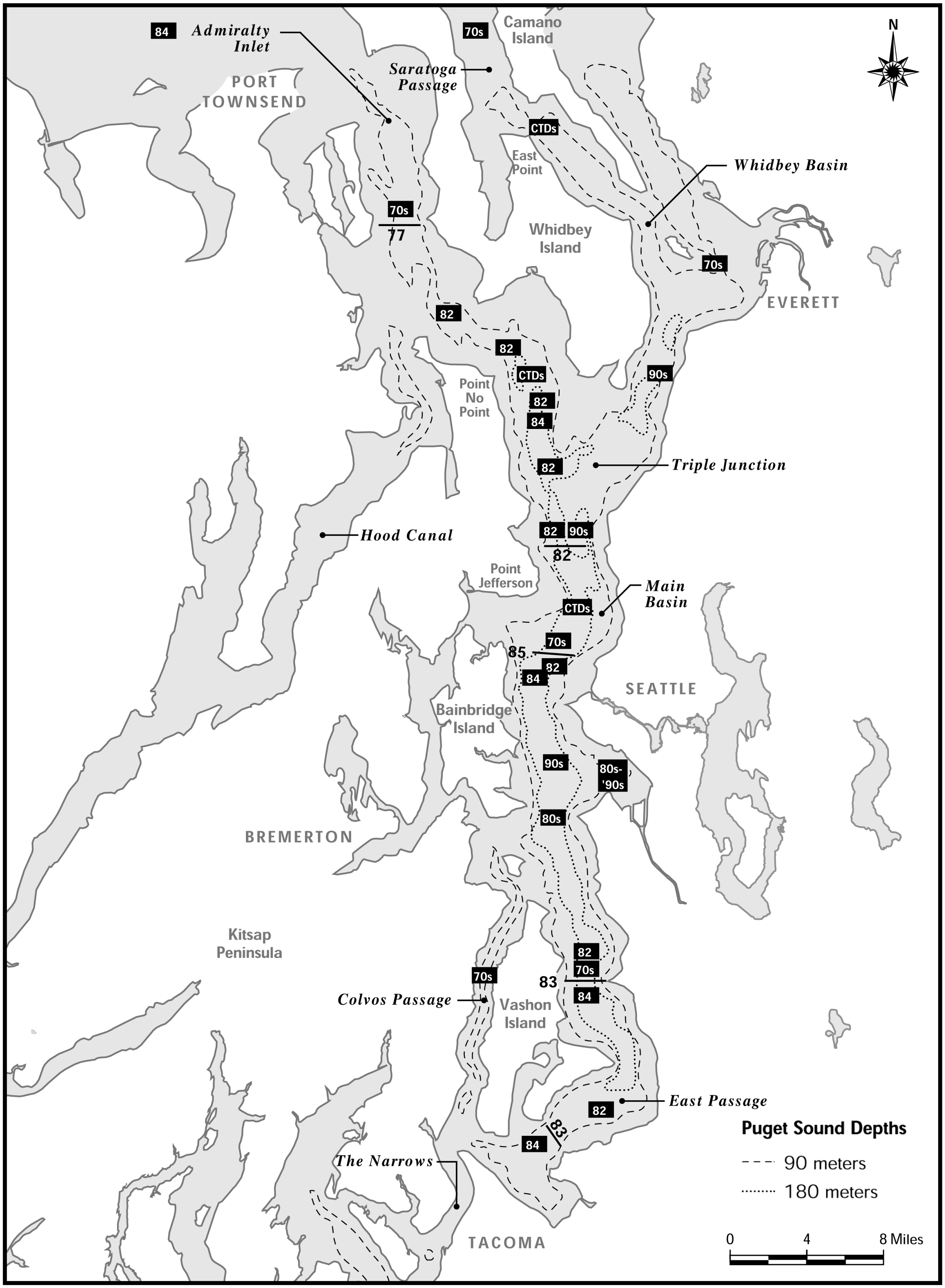

Figure 1 Chart of Puget Sound showing historical current meter moorings (dates) and hydrographic stations (CTD at Point Jefferson in the Main Basin, Point no Point in Admiralty Inlet, and East Point in Saratoga Passage). Cross channel transects in ’77, ’82, ’83, and ‘85

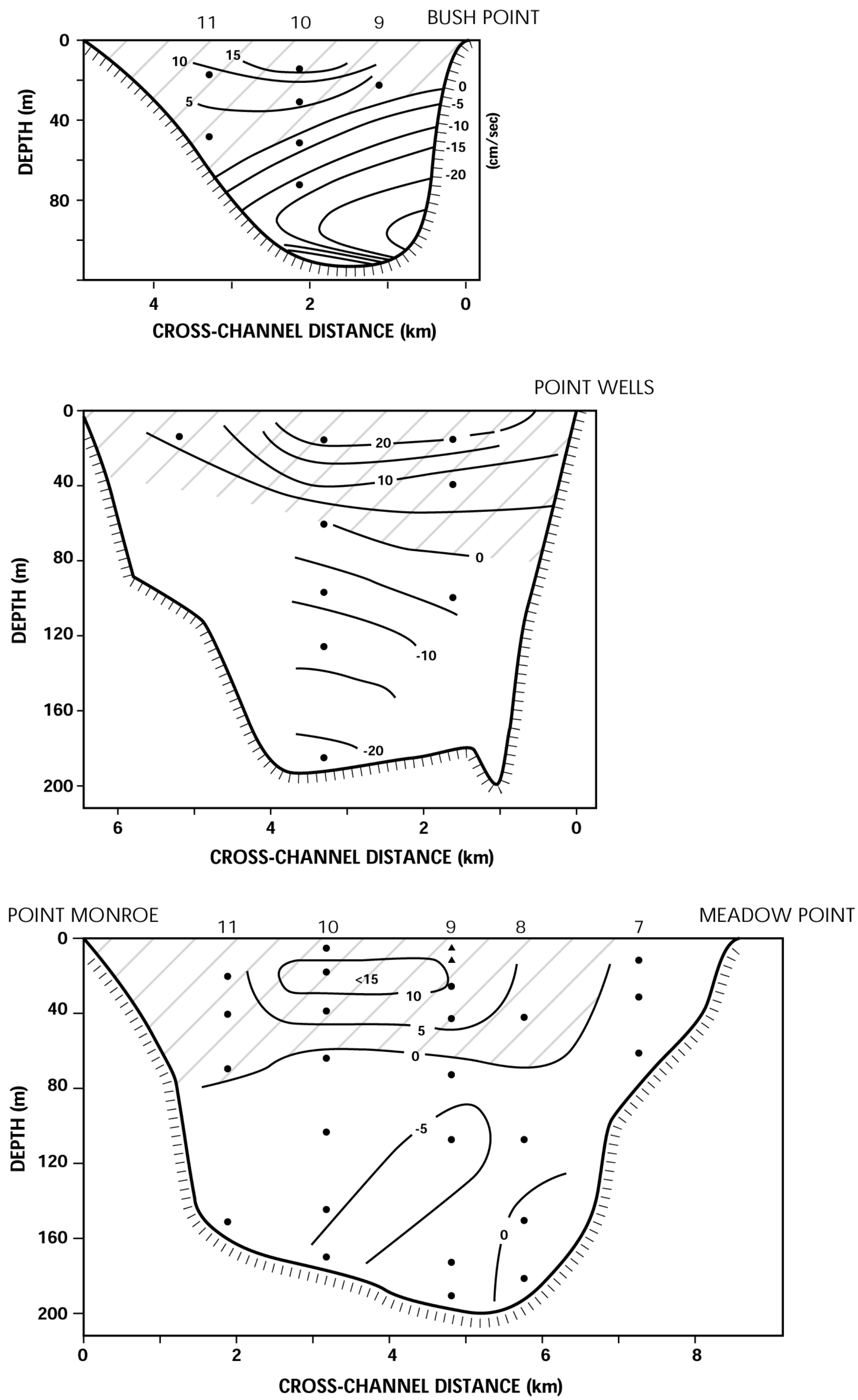

Figure 2 Cross sections of mean currents in Admiralty Inlet ('77, upper), in the Main Basin at Point Wells ('82, middle), and at Meadow Point ('85, lower). Dots show current meter locations. The level of zero mean flow (change from inflow to outflow) varies across each section and between sections.

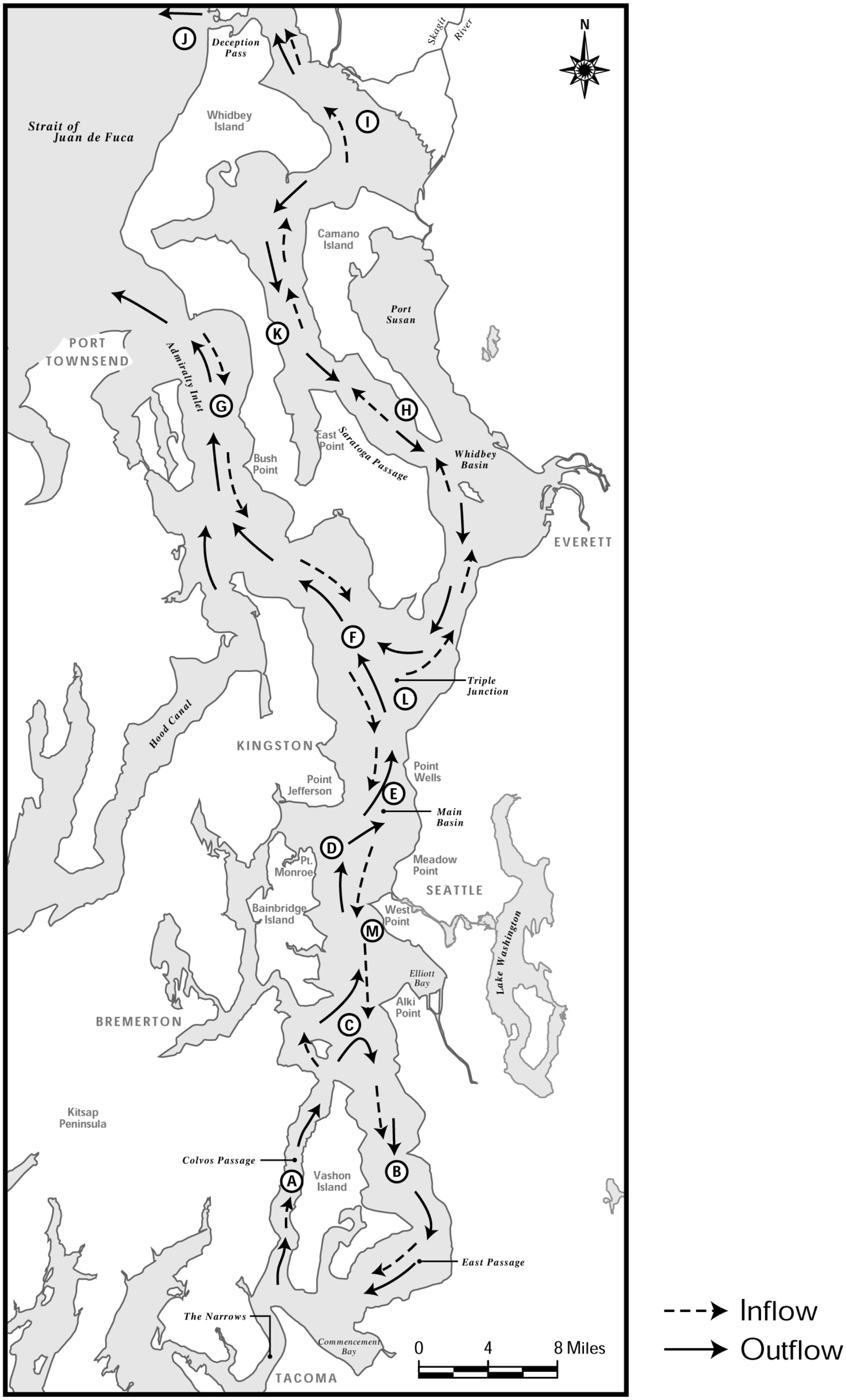

Figure 3. Schematic plan view of shallow (solid arrows) and deep (dashed arrows) estuarine circulation (tides averaged out) in the Main and Whidbey basins. Flow features are described in text.

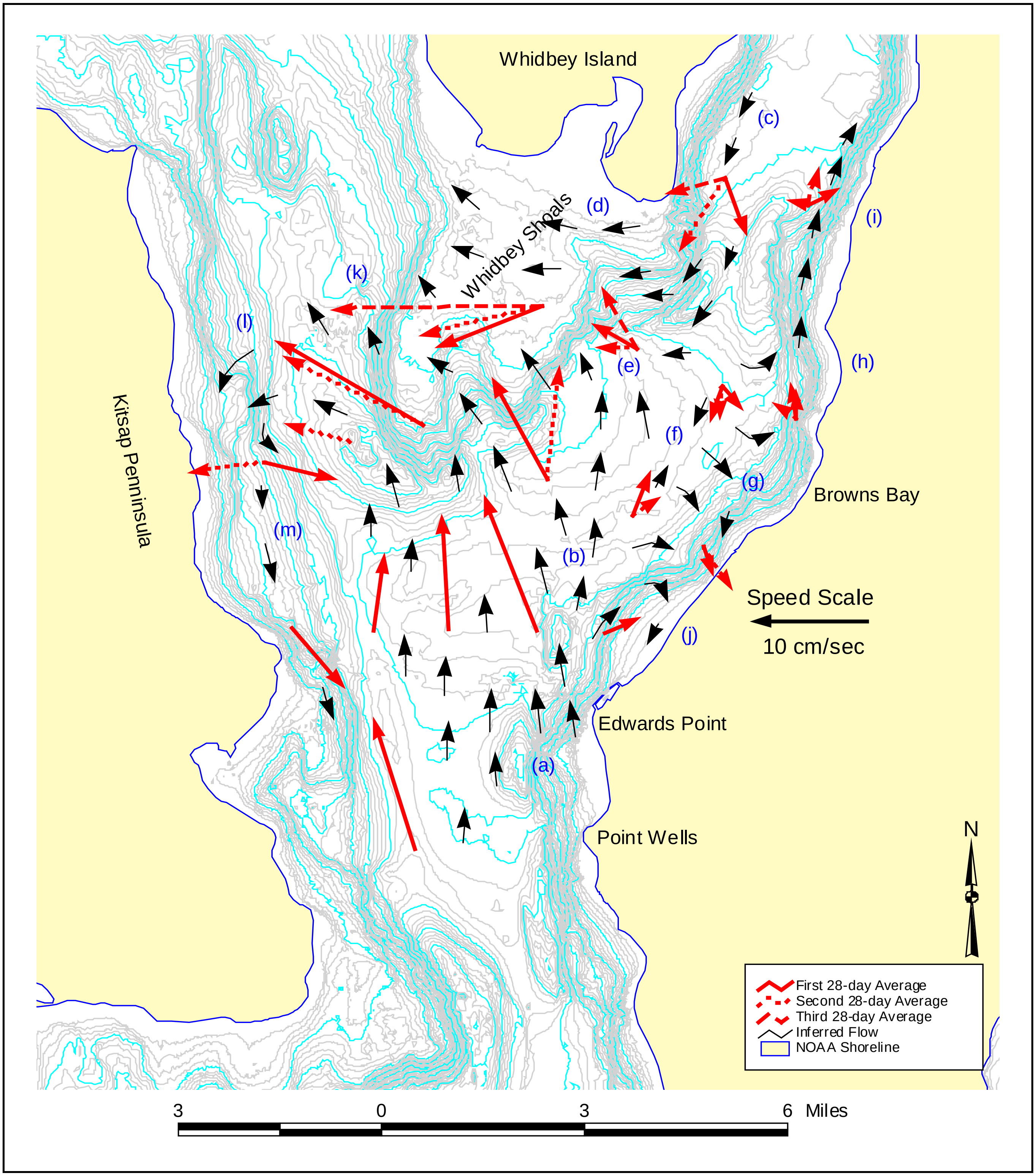

Figure 4 Net velocity vectors at 20 m for July 2000 through January 2001. Flow details are explained in text. Red arrows are measured currents; black inferred.

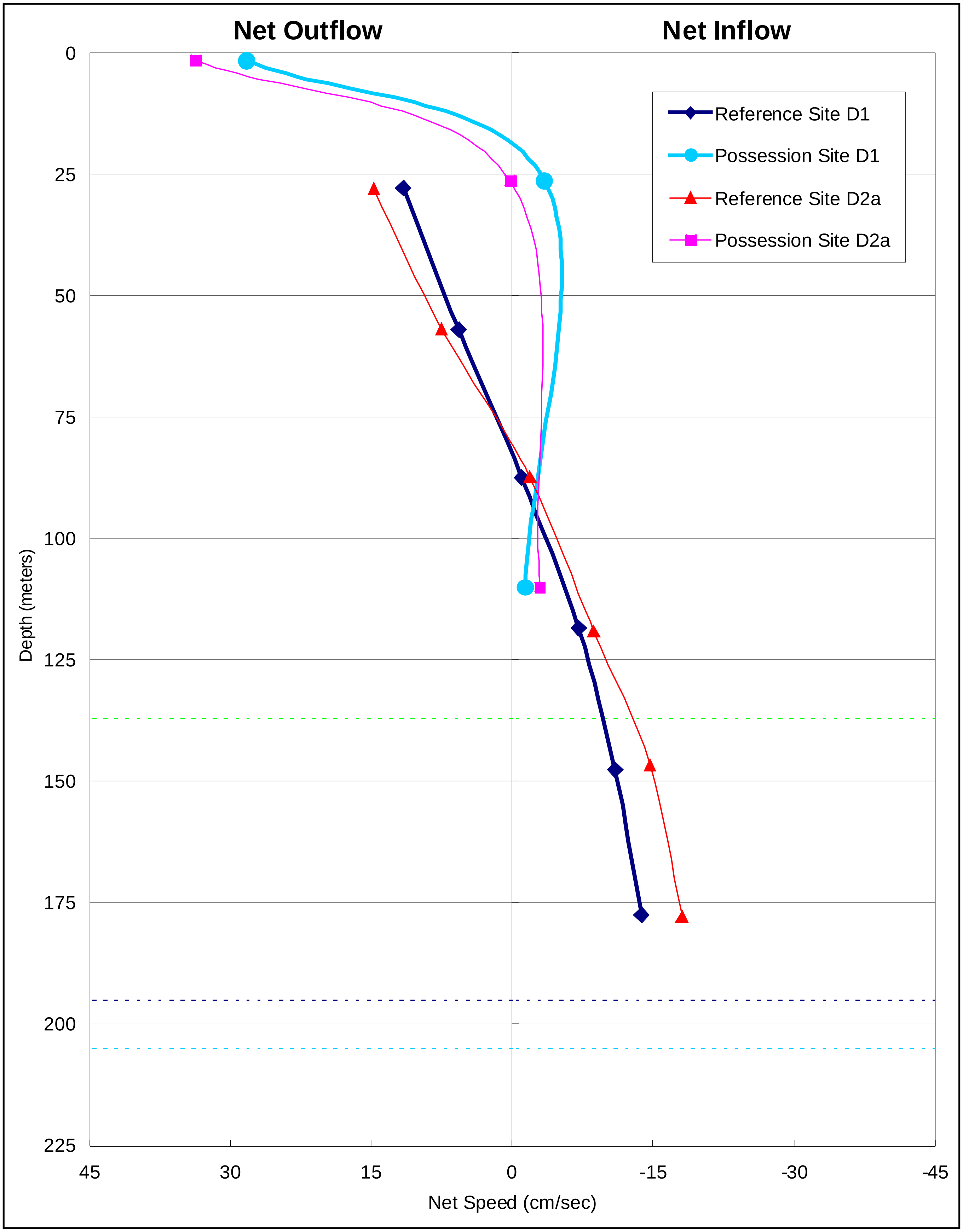

Figure 5 Net speed along-channel at the Reference and Possession Sound moorings. Dates: D1, 7/13 – 8/9/2000; D2a, 8/25 – 9/21/2000. Dotted lines represent sea floor.

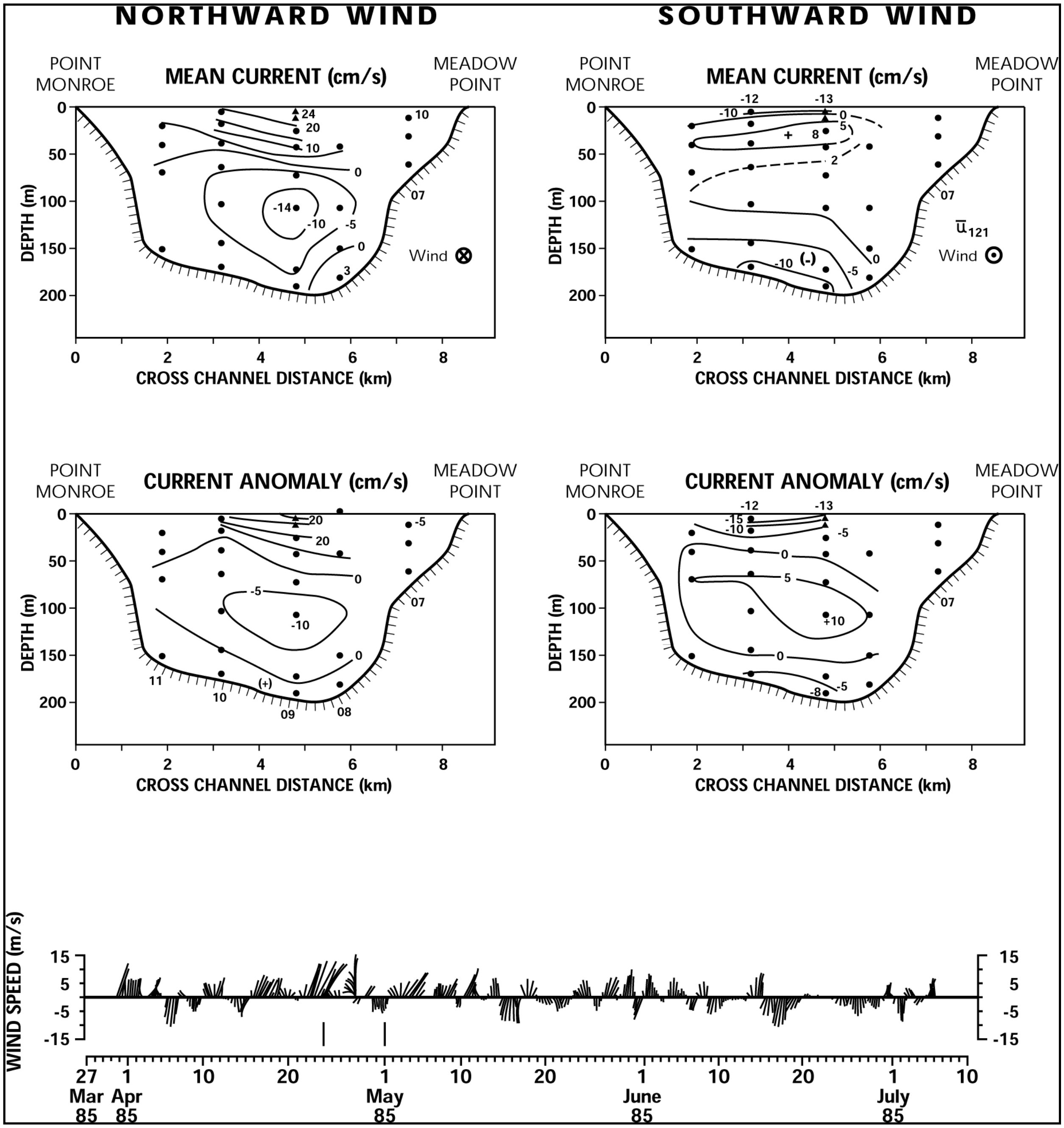

Figure 6 Wind effects on mean circulation in the main basin during northward and southward winds. Upper panels show daily average along channel currents on April 24 and May 1; the middle panels show differences in speeds between each of these days and the long-term means for the section. Lower panel shows low-frequency winds noting times of northward and southward winds.

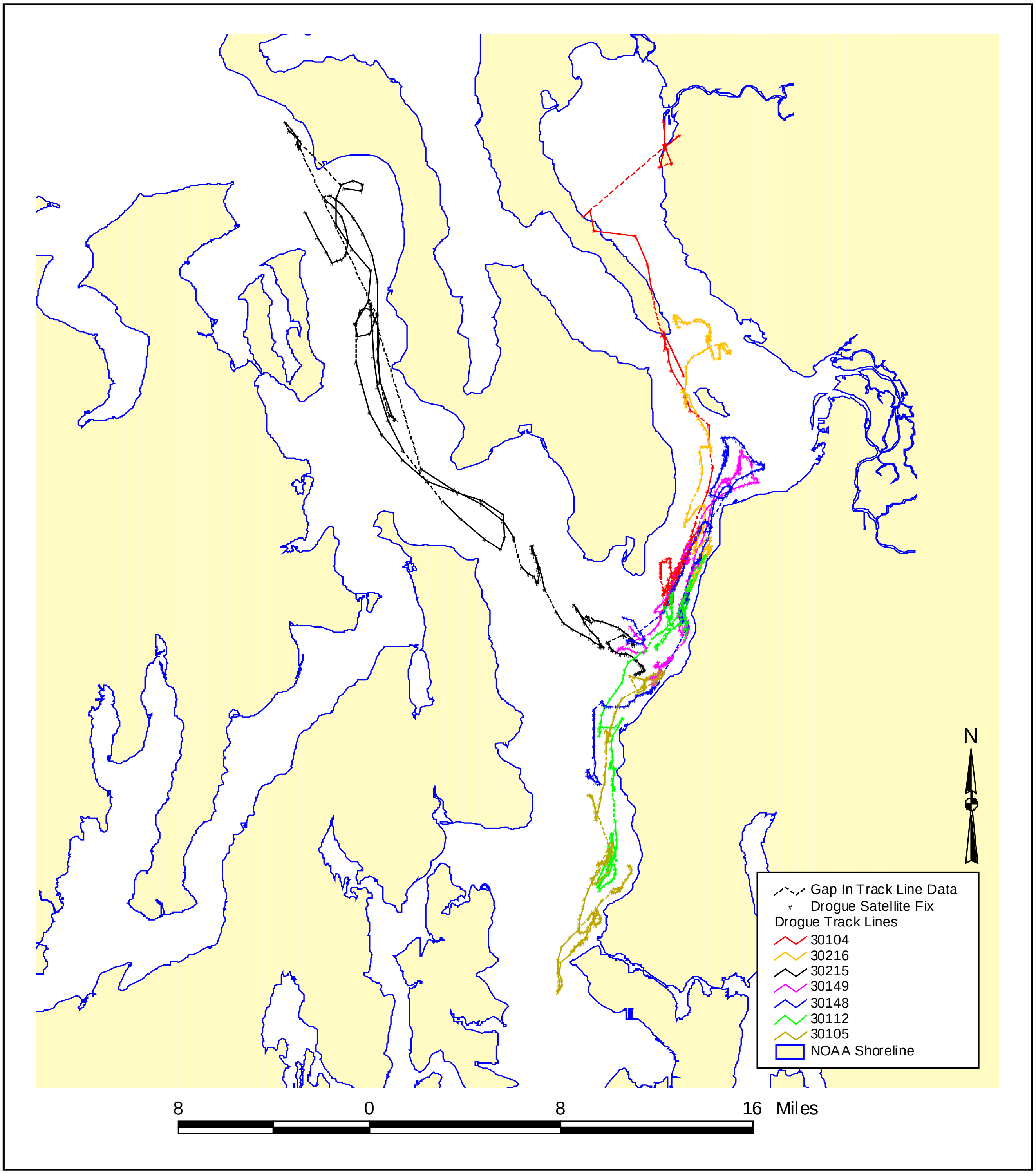

Figure 7 Drogue trajectories October 25 through 31, 2000. Depths were 20 to 30 m.

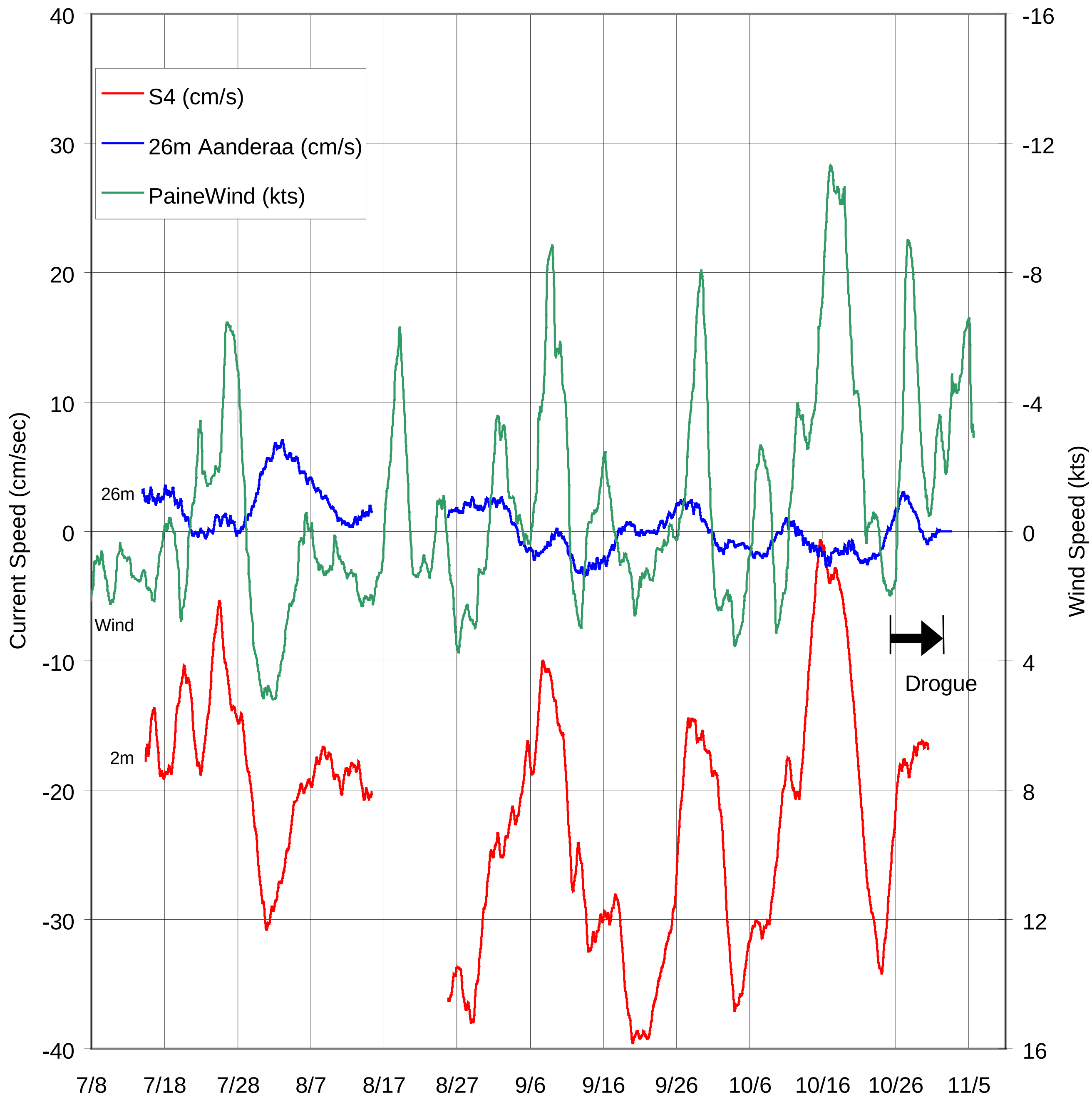

Figure 8 Net along-channel currents at 2 and 26 m in Possession Sound and winds at Paine Field during July – November, 2000. Drogues were deployed October 25 through 31.

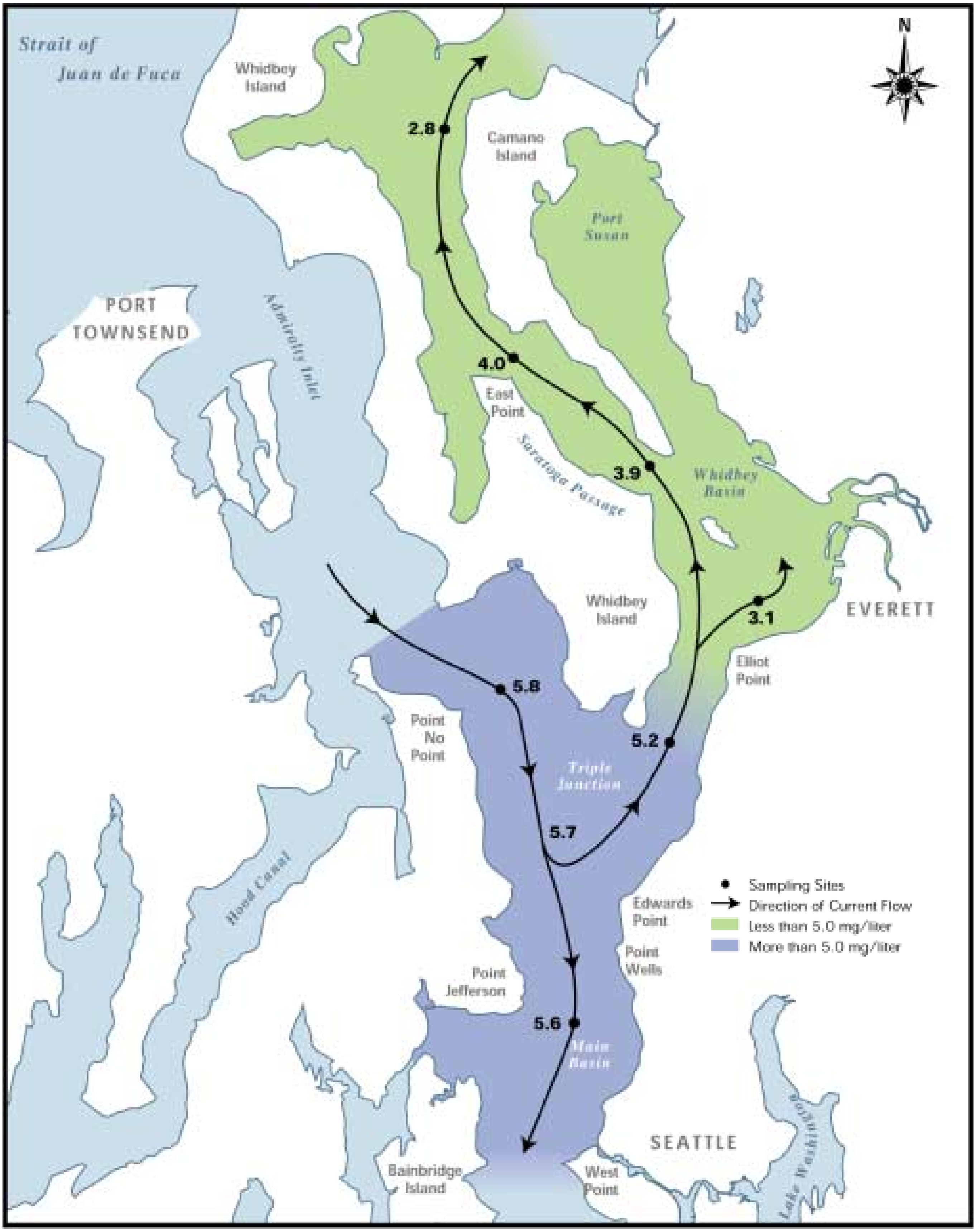

Figure 9 Lowest observed dissolved oxygen in the deep water of the Main Basin and Whidbey Basin during September through October (from historical data). A significant decrease occurs in Possession Sound.